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RESEARCH MEMORANDUM

EFFECT OF VARIATION IN FUEL PRESSURE ON COMBUSTION PERFORMANCE OF RECTANGULAR RAM JET

By Wesley E. Messing and Dugald O. Black

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The results of an investigation conducted on a rectangular ram jet to determine the effect of variation in fuel pressure on the starting characteristics, minimum blow-out limits, combustion efficiencies, gas total-temperature ratio, and net-thrust coefficient are presented and discussed. The ram jet was operated over a range of pressure altitudes from 1500 to 26,300 feet, indicated airspeeds from 100 to 200 miles per hour, and fuel-air ratios from 0.017 to 0.120. Three different sets of fuel nozzles were used (21.5, 30.0, and 40.0 gal/hr at a pressure differential of 100 lb/sq in.) in order to obtain a range of fuel pressures for a given fuel flow.

Increasing the degree of fuel atomization and distribution by utilization of small-orifice fuel nozzles that operated at high fuel pressures resulted in higher values of combustion efficiency, gas total-temperature ratio, and net-thrust coefficient at a given fuel-air ratio. A maximum fuel pressure was encountered at a given engine air flow for the highest value of combustion efficiency, whereas a further increase in fuel pressure was detrimental because the fuel particles had sufficient momentum to strike and flow along the combustion-chamber wall instead of uniformly mixing with the engine-air flow. When the fuel pressure was increased, the maximum combustion efficiency occurred at lower values of fuel-air ratio. For the same flight condition, the ram jet could be started at lower values of fuel-air ratio when the small-orifice nozzles operating at high fuel pressures were used.

INTRODUCTION

In order to obtain combustion with high efficiency in a ram jet, the fuel stream must be finely atomized. As shown in reference 1, fuel leaves a nozzle as an unbroken column that is quickly disintegrated into many irregular parts by one or a combination of the following factors: fuel-stream turbulence, vorticity, impingement, and forces resulting from the relative motion between the fuel and the air. For a given fuel-flow rate, the degree of atomization can be increased by increasing the jet velocity of the fuel by means of nozzles with smaller orifice diameters.

An investigation has been completed at the NACA Cleveland laboratory to determine the effect of a variation in fuel pressure on the performance of a rectangular ram jet using three sets of fuel nozzles. Inasmuch as the three sets of nozzles had different orifice diameters and therefore were rated at different flow capacities, identical fuel flows could be obtained only with a wide variation in fuel-discharge pressure, which resulted in different fuel jet velocities at any given fuel flow. The ram jet was operated in flight over a range of pressure altitudes from 1500 to 26,300 feet, indicated airspeeds from 100 to 200 miles per hour, and fuel-air ratios from 0.017 to 0.120 for three different sets of commercial fuel-spray nozzles rated at 21.5, 30.0, and 40.0 gallons per hour at a pressure differential of 100 pounds per square inch. Results obtained in previous parts of this extensive investigation of the rectangular ram jet are presented in references 2 to 4.

APPARATUS AND PROCEDURE

A complete description of the rectangular ram jet and the instrumentation is given in reference 3. The rectangular ram jet consists of a diffuser, a fuel-spray bar, a shielded spark-plug igniter, a four-V gutter-type flame holder, and a combustion chamber (fig. 1). The ram jet was installed beneath the fuselage of a twin-engine fighter-type airplane, as shown in figure 2. The engine air flow was calculated from total and static pressures measured at the diffuser by three total- and static-pressure rakes, eighteen static-pressure wall orifices, and from the ambient-air temperature measured by a flight-calibrated iron-constantan thermocouple. The flow conditions at the combustion-chamber outlet were measured by a water-cooled total-pressure rake and two static-pressure wall orifices. Indicated airspeed and pressure altitude were measured by aircraft indicators connected to a swiveling static-pressure tube and a shrouded total-pressure tube installed on a boom 1-chord length ahead of the leading edge of the right wing tip. Fuel flow was measured by a vane-type flowmeter and the fuel pressures at the pump outlet and the inlet to the combustion-chamber manifold were indicated by gages.

The fuel nozzles used in this investigation consisted of three sets of six evenly spaced commercial spray nozzles. The nozzles had

1034 a discharge rate per nozzle of 21.5, 30.0, and 40.0 gallons per hour at a pressure differential of 100 pounds per square inch gage and discharged downstream in a 60° hollow vortical cone under a no-air-flow condition. The fuel used for this investigation was AN-F-23a (73-octane gasoline).

The data were calculated in accordance with the methods presented in references 3 and 4.

Ram-jet combustion data were obtained with each fuel-nozzle configuration at pressure altitudes of 1500, 6000, 16,000, and 26,000 feet. Flight investigations were conducted at an indicated airspeed of 200 miles per hour at all altitudes except 26,000 feet, where the airspeed was reduced to 160 miles per hour in order to avoid rough engine operation. When the 21.5-gallon-per-hour fuel nozzles were used, however, a complete fuel-air-ratio range could not be obtained because only relatively low fuel flows could be obtained at the maximum fuel pressure (400 lb/sq in. gage). In order to complete the fuel-air ratio range, the engine air flow was decreased by decreasing the indicated airspeed to 160 miles per hour and supplementary data were taken.

RESULTS AND DISCUSSION

The engine operated without excessive noise or vibration at altitudes of 1500 and 6000 feet with each fuel-nozzle configuration. At 16,000 feet, rough operation was encountered with the 40.0-gallon-per-hour fuel nozzles as the fuel-air ratio approached the lean blow-out limit. When this flight was repeated with 30.0- and 21.5-gallon-per-hour fuel nozzles, combustion remained smooth as the fuel-air ratio was reduced to the lean blow-out limit, which indicated that the rough operation previously encountered resulted from the relatively low degree of fuel atomization and distribution produced by the 40.0-gallon-per-hour fuel nozzles. At an altitude of 26,000 feet and an indicated airspeed of 160 miles per hour, rough engine operation was encountered with each fuel-nozzle configuration as the fuel-air ratio approached the rich blow-out limit.

The starting characteristics of the ram jet for each fuel-nozzle configuration are shown in table I. Improving the degree of fuel atomization and distribution by the utilization of nozzles with smaller orifice diameters resulted, in general, in easier starting with ignition occurring at lower values of fuel-air ratio for a given flight condition. The ram jet could not be started above 22,250 feet with the 40.0-gallon-per-hour nozzles, although ignition was easily accomplished at 25,600 and 26,300 feet with the 21.5- and 30.0-gallon-per-hour fuel nozzles, respectively.

The fuel pressures obtained at the inlet to the combustion-chamber fuel manifold are presented in figure 3 as a function of fuel-air ratio for each nozzle configuration and flight condition. These fuel-pressure data are applicable to subsequent curves on combustion efficiency, gas total-temperature ratio, and net-thrust coefficient.

The effect of fuel-air ratio on combustion efficiency for the 21.5-, 30.0-, and 40.0-gallon-per-hour fuel nozzles and pressure altitudes of 1500, 6000, 16,000, and 26,000 feet is presented in figure 4. The general trend noted is that for a given operating condition there is an optimum-size fuel nozzle with a corresponding fuel pressure that results in the degree of fuel atomization and distribution necessary for the most favorable combustion. At an altitude of 1500 feet and a fuel-air ratio of 0.03, the 21.5-gallon-per-hour nozzles operating at a fuel pressure of 195 pounds per square inch resulted in a combustion efficiency of 71 percent, which is an improvement over a combustion efficiency of 39 percent obtained with the 40.0-gallon-per-hour nozzles operating at a lower fuel pressure of 77 pounds per square inch. For a given ram-jet configuration and operating condition, however, there is a maximum value of fuel pressure for the highest combustion efficiency, at which point a further increase in fuel pressure can be detrimental if the momentum of the fuel particles is sufficient that the fuel strikes the combustion chamber and flows along the wall instead of mixing with the engine air flow. For example, this phenomenon is believed to exist at an altitude of 1500 feet and a fuel-air ratio of 0.06. At this operating condition, the 21.5-gallon-per-hour nozzles operating at a fuel pressure of 340 pounds per square inch resulted in a combustion efficiency of only 62 percent. When the ram jet was operated with the 30-gallon-per-hour nozzles at a fuel pressure of 230 pounds per square inch, the combustion efficiency was increased to 80 percent. When the fuel pressure was further reduced to 150 pounds per square inch by using the 40-gallon-per-hour nozzles, the combustion efficiency decreased slightly to 75 percent. For all altitudes, the peak in the combustion efficiency curve occurs at lower values of fuel-air ratio for the 21.5-gallon-per-hour nozzles than the 30-gallon-per-hour nozzles and the peak combustion efficiency for the 30-gallon-per-hour nozzles occurs at lower values of fuel-air ratio than the 40-gallon-per-hour nozzles.

For the operating range of this investigation, the maximum or peak combustion efficiency occurred as shown in the following table at the designated fuel-air ratios and fuel pressures:

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Fuel-nozzle flow capacity at 100 lb/sq in. (gal/hr)	Pressure altitude (ft)	Combustion efficiency (percent)	Fuel-air ratio	Fuel pressure (lb/sq in. gage)
21.5	1,500	82	0.0365	240
	6,000	82	.0455	280
	16,000	70	.0600	278
	26,000	36	.0760	192
30	1,500	91	0.0495	167
	6,000	82	.0550	165
	16,000	45	.0720	195
	26,000	29	.0820	110
40	1,500	75	0.0600	150
	6,000	61	.0670	167
	16,000	44	.0730	145
	26,000	29	.0900	80

The highest combustion efficiencies for each nozzle configuration occurred at the low altitudes and, in general, an increase in altitude resulted in a decrease in combustion efficiency. The tailed symbols in figure 4 indicate the fuel-air ratio at which lean blow-out occurred. This blow-out fuel-air ratio is defined as the ratio of the fuel flow at blow-out to the engine air flow immediately preceding blow-out. For almost all cases, the ram jet could be operated at lower fuel-air ratios with the 40-gallon-per-hour nozzles than with the 30-gallon-per-hour nozzles; and the 30-gallon-per-hour nozzles could support combustion at lower fuel-air ratios than the 21.5-gallon-per-hour nozzles. At low values of fuel-air ratio, the 40-gallon-per-hour nozzles operate at very low fuel pressures in a relatively high-velocity air stream. This condition tends to decrease the fuel cone as the fuel sprays from the nozzles and produces a rich fuel-air ratio along the center line of the flame holder that is capable of supporting combustion, although the over-all fuel-air ratio is low. Because of this rich-mixture region, the blow-out fuel-air ratio of the 40.0-gallon-per-hour nozzle is lower than that of the 30.0- and 21.5-gallon-per-hour nozzles, which operate at higher fuel pressures for a given fuel flow and therefore result in more uniform fuel distribution.

The effect of fuel-air ratio on gas total-temperature ratio is shown in figure 5 for the 21.5-, 30.0-, and 40.0-gallon-per-hour fuel nozzles operated at altitudes of 1500, 6000, 16,000, and 26,000 feet. At the higher altitudes (16,000 and 26,000 ft), there was a decided advantage to operation at high fuel pressures with the 21.5-gallon-per-hour nozzles, because for all fuel-air ratios the highest gas total-temperature ratios were obtained with these nozzles. For example, at 16,000 feet and a fuel-air ratio of 0.06, use of the 21.5-gallon-per-hour nozzle resulted in a gas total-temperature ratio of 6.0 at a fuel pressure of 278 pounds per square inch as compared with a gas total-temperature ratio of 4.4 for the 30.0- and 40.0-gallon-per-hour nozzles operating at fuel pressures of 158 and 115 pounds per square inch, respectively. In general, at the lower altitudes (1500 and 6000 ft), higher gas total-temperature ratios were obtained with the 21.5-gallon-per-hour nozzles at fuel-air ratios below 0.035. Use of the 30-gallon-per-hour nozzles resulted in higher gas total-temperature ratios at fuel-air ratios of 0.035 to 0.065; above 0.065 the 40-gallon-per-hour nozzles resulted in the highest gas total-temperature ratio. The highest gas total-temperature ratios encountered were from approximately 6.5 to 6.6 and occurred with the 21.5-gallon-per-hour nozzles at 16,000 feet and a fuel-air ratio of 0.070 at a fuel pressure of 340 pounds per square inch, with the 30-gallon-per-hour nozzles at 6000 feet and a fuel-air ratio of 0.065 at a fuel pressure of 215 pounds per square inch, and with the 40-gallon-per-hour nozzles at 1500 feet and a fuel-air ratio of 0.075 at a fuel pressure of 215 pounds per square inch.

The effects of fuel-air ratio on the net-thrust coefficient for the different fuel-nozzle configurations at pressure altitudes of 1500, 6000, 16,000, and 26,000 feet are presented in figure 6. The general trends noted in figure 5 are repeated. For all conditions, it is apparent that as the fuel-air ratio was increased from the lean blow-out value a rapid increase in net-thrust coefficient was followed by a gradual leveling of the curve. The effect of increasing the fuel pressure by utilizing a smaller-orifice nozzle decreased the value of fuel-air ratio at which the maximum net-thrust coefficient first occurred. At altitudes of 16,000 and 26,000 feet, the higher fuel pressures that occurred with the 21.5-gallon-per-hour nozzles resulted in higher values of net-thrust coefficient at any given fuel-air ratio. At 16,000 feet and a fuel-air ratio of 0.07 and fuel pressure of 340 pounds per square inch, use of the 21.5-gallon-per-hour nozzles resulted in a net-thrust coefficient of 0.405, which was approximately a 29-percent improvement over a net-thrust coefficient of 0.315 obtained with the 40-gallon-per-hour nozzles operating at a fuel pressure of 138 pounds per square inch. This improvement is attributed solely to the increased degree of atomization and distribution of the fuel attained with the smaller orifice nozzles operating at higher fuel pressures.

SUMMARY OF RESULTS

From a flight investigation conducted on a rectangular ram jet incorporating separate sets of 21.5-, 30.0-, and 40.0-gallon-per-hour fuel nozzles, the following results were obtained over a range of pressure altitudes from 1500 to 26,300 feet, indicated airspeeds from 100 to 200 miles per hour, and fuel-air ratios from 0.017 to 0.120:

1. Increasing the degree of fuel atomization and distribution by utilization of small-orifice nozzles that operated at high fuel pressures generally resulted in higher values of combustion efficiency, gas total-temperature ratio, and net-thrust coefficient at a given fuel-air ratio. Maximum fuel pressure, however, was encountered at a given engine air flow for the highest value of combustion efficiency, whereas a further increase in fuel pressure was detrimental because the fuel particles had sufficient momentum to strike and flow along the combustion-chamber wall instead of uniformly mixing with the engine air flow.

2. For all altitudes, the peak in the combustion efficiency curve occurred at lower values of fuel-air ratio for the 21.5-gallon-per-hour nozzles than for the 30-gallon-per-hour nozzles and the peak combustion efficiency for the 30-gallon-per-hour nozzles occurred at lower values of fuel-air ratio than the 40-gallon-per-hour nozzles.

3. The most noticeable increase in gas total-temperature ratio with increasing fuel pressure occurred at an altitude of 16,000 feet and a fuel-air ratio of 0.06. The 21.5-gallon-per-hour nozzles, operating at a fuel pressure of 278 pounds per square inch, resulted in a gas total-temperature ratio of 6.0 as compared with a value of 4.4 obtained with the 40-gallon-per-hour nozzles at a fuel pressure of 115 pounds per square inch.

4. For the same flight conditions, the ram jet could be started at lower values of fuel-air ratio when the small-orifice nozzles operating at higher pressures were used.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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1. Lee, Dana W.: The Effect of Nozzle Design and Operating Conditions on the Atomization and Distribution of Fuel Sprays. NACA Rep. No. 425, 1932.

2. Black, Dugald O., and Messing, Wesley E.: Test-Stand Investigation of a Rectangular Ram-Jet Engine. NACA RM No. E7D11, 1947.

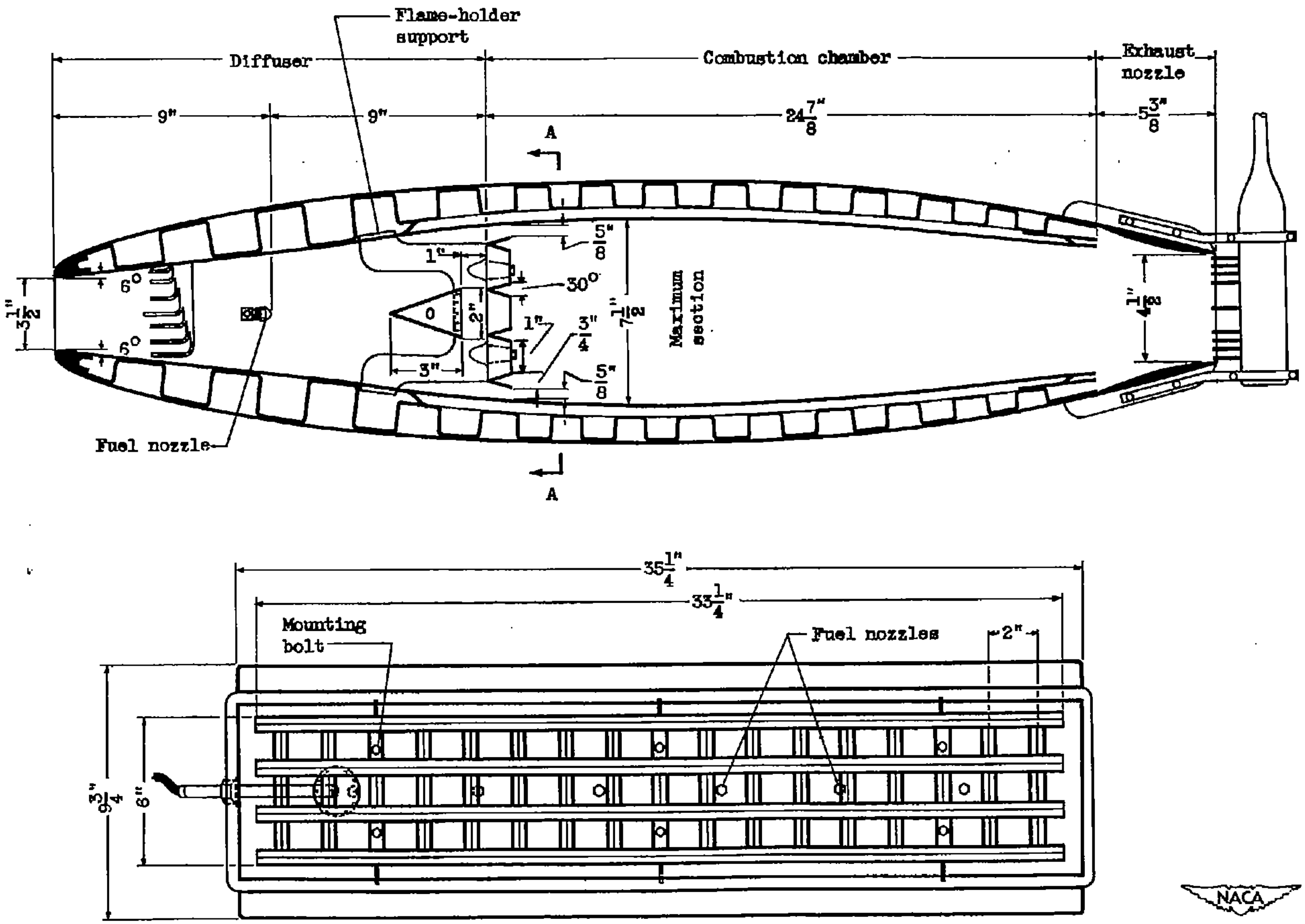
3. Messing, Wesley E., and Black, Dugald, O.: Subsonic Flight Investigation of Rectangular Ram Jet over Range of Altitudes. NACA RM No. E7H26, 1948.

4. Black, Dugald O., and Messing, Wesley E.: Effect of Various Flame-Holder Configurations on Subsonic Flight Performance of Rectangular Ram Jet over Range of Altitudes. NACA RM No. E8I01, 1948.

TABLE I - STARTING CHARACTERISTICS OF RAM JET FOR

THREE FUEL-NOZZLE CONFIGURATIONS

Altitude (ft)	Indicated airspeed (mph)	Fuel-air ratio
21.5-gal/hr fuel nozzles (at 100 lb/sq in.)		
1500	160	0.019
1500	200	.021
6000	160	.020
6000	200	.022
16,000	125	.057
21,000	100	.062
25,600	100	.082
30.0-gal/hr fuel nozzles (at 100 lb/sq in.)		
1500	200	0.025
6000	200	.029
21,000	100	.071
21,000	110	.089
23,900	108	.102
24,800	100	.080
26,300	100	.120
40.0-gal/hr fuel nozzles (at 100 lb/sq in.)		
1500	200	0.028
3000	200	.036
6000	200	.038
11,000	160	.038
11,000	160	.044
16,000	160	.052
18,000	125	.067
22,250	115	.078



Section A-A

Figure 1. - Schematic diagram of rectangular ram jet incorporating four-V gutter-type flame holder.

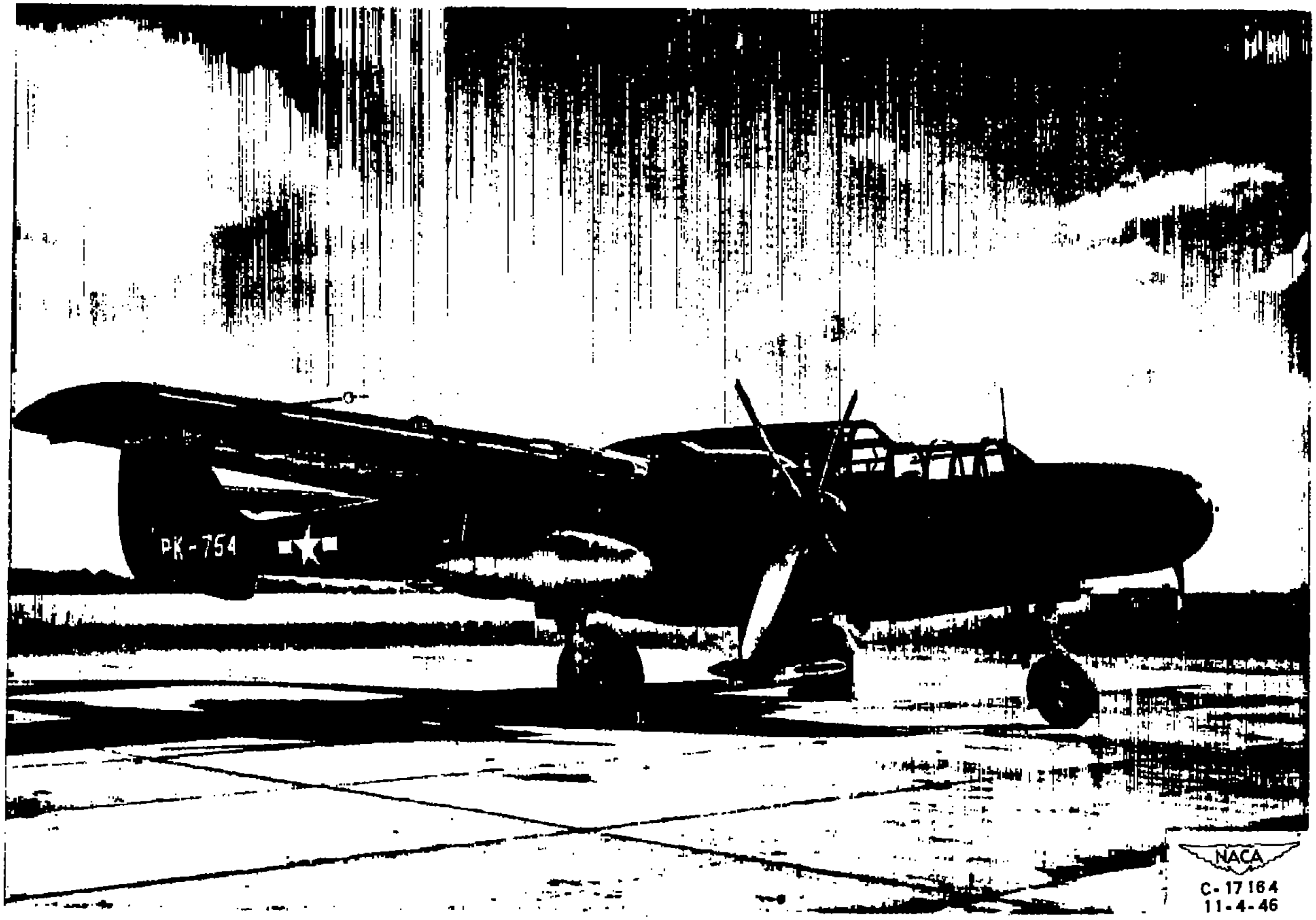


Figure 2. - Rectangular ram jet installed beneath airplane fuselage.

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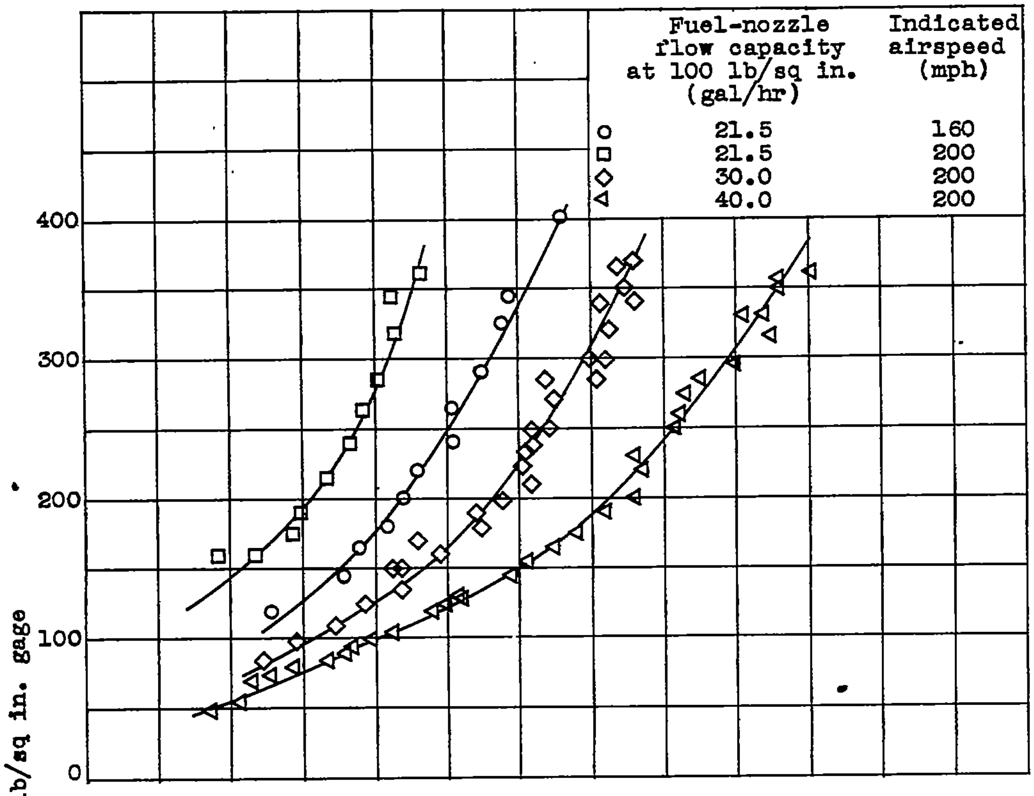
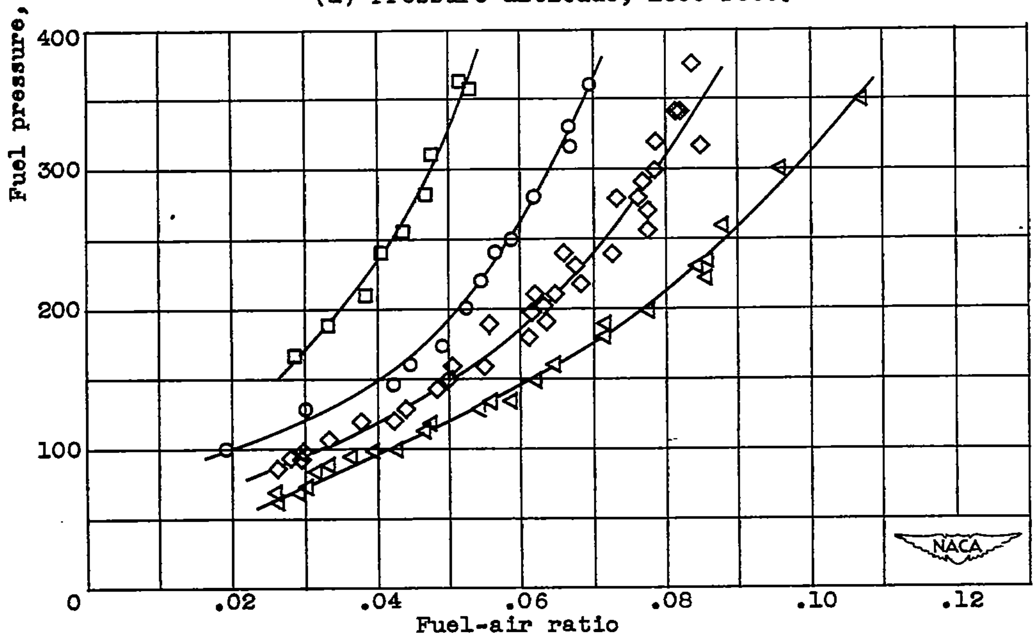
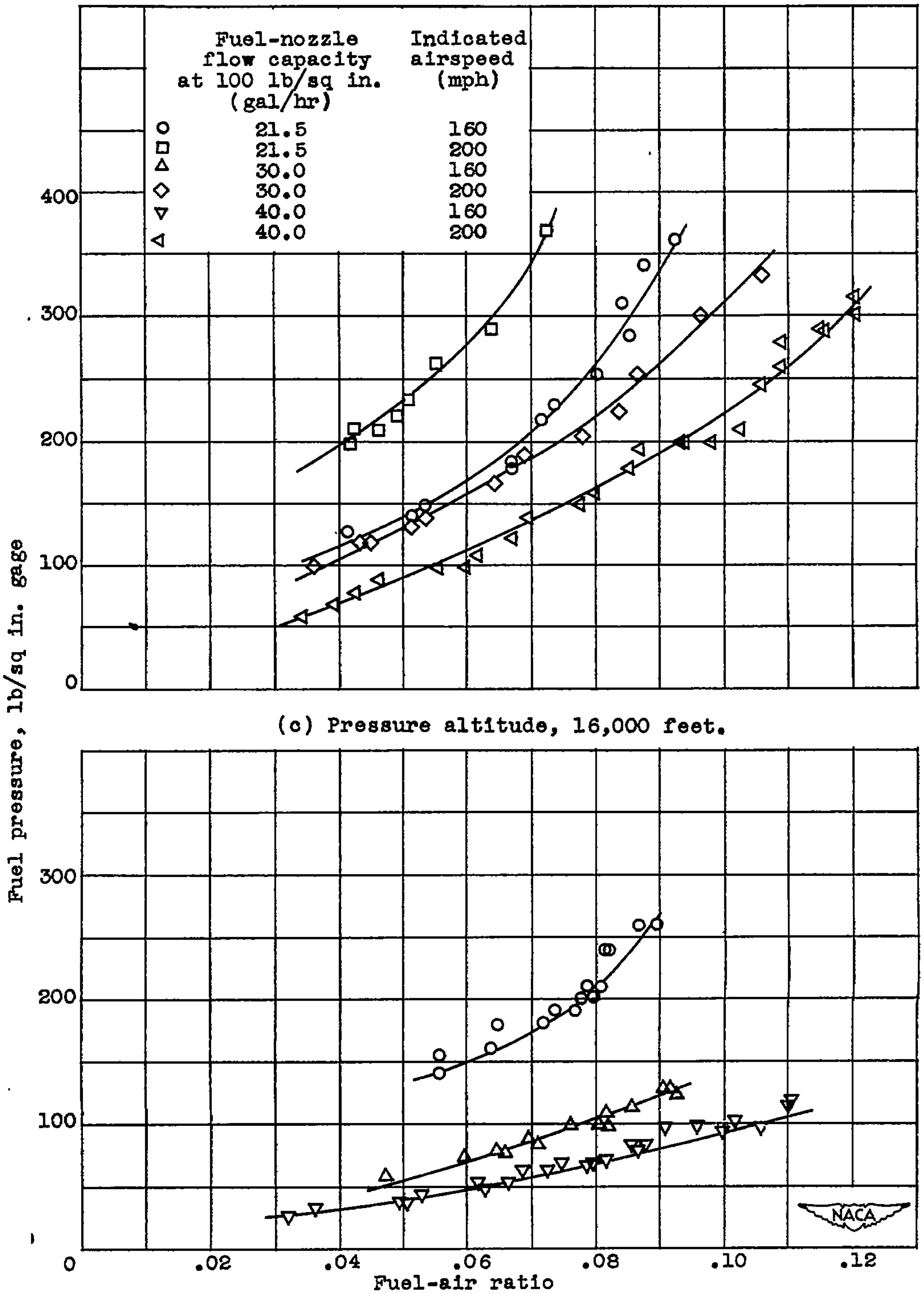


(a) Pressure altitude, 1500 feet.



(b) Pressure altitude, 6000 feet.

Figure 3. - Measured fuel pressure obtained with rectangular ram jet for operating range of fuel-air ratios.



(d) Pressure altitude, 26,000 feet.

Figure 3. - Concluded. Measured fuel pressure obtained with rectangular ram jet for operating range of fuel-air ratios.

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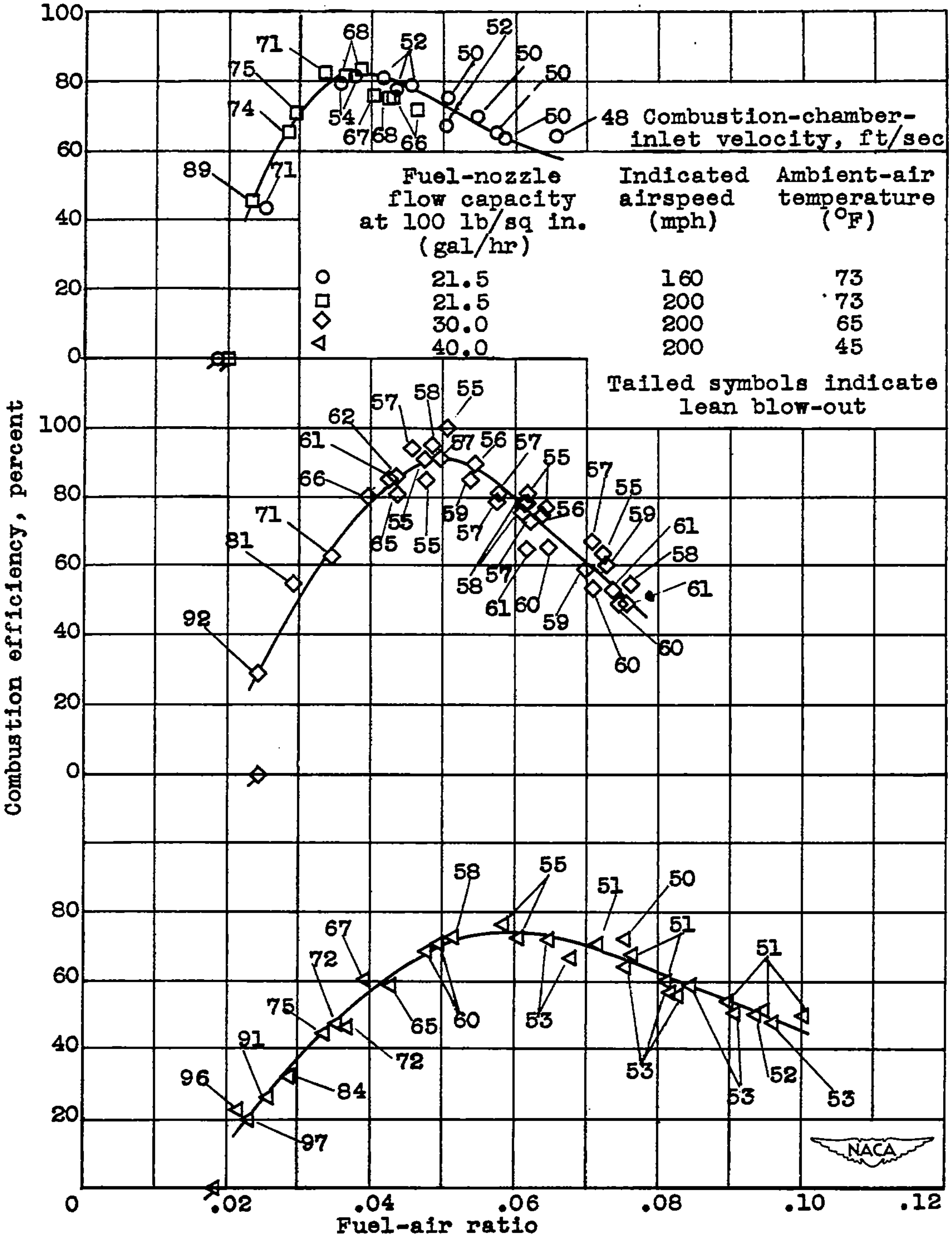
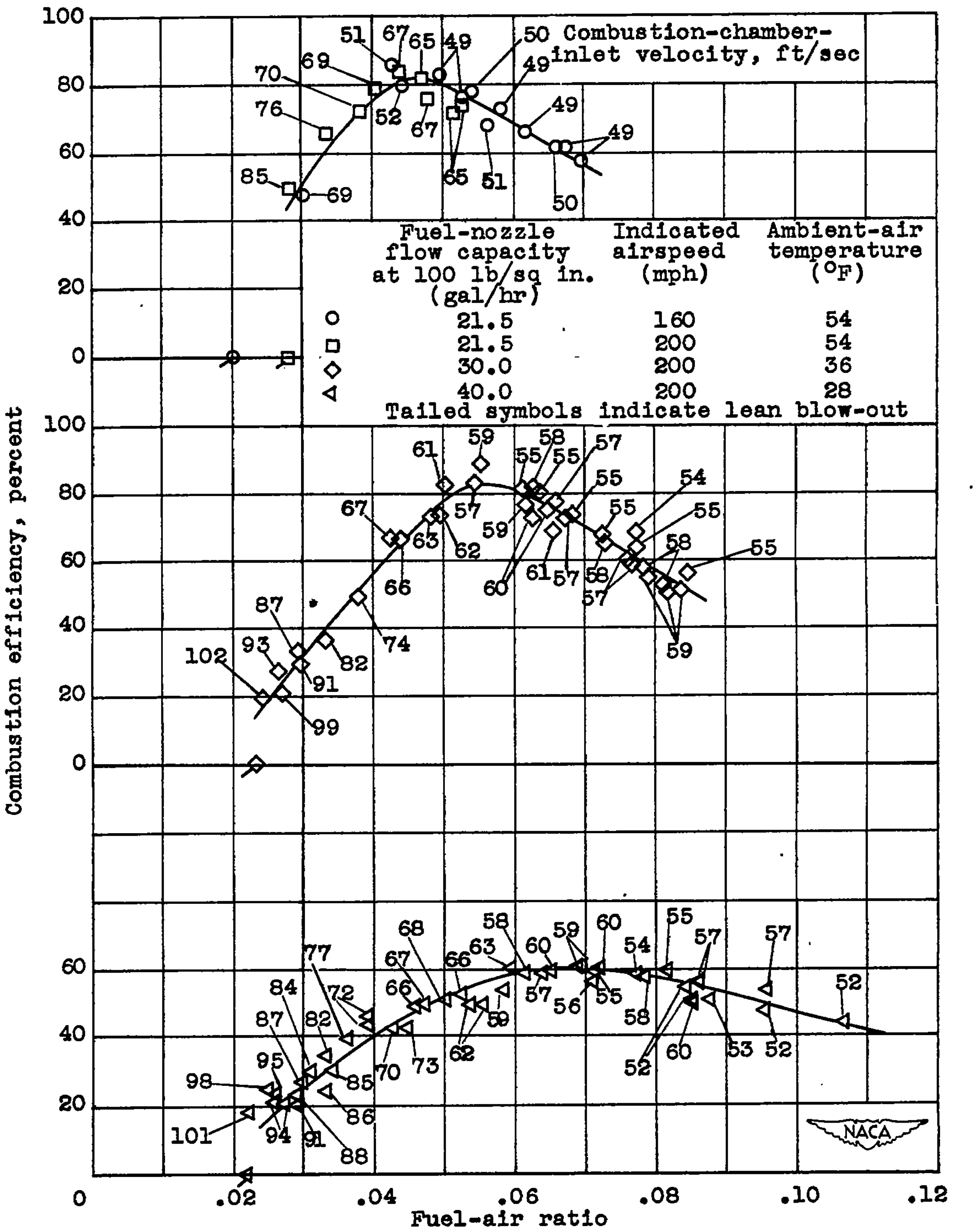


(a) Pressure altitude, 1500 feet.

Figure 4. - Effect of fuel-air ratio and fuel-nozzle configuration on combustion efficiency of rectangular ram jet.



(b) Pressure altitude, 6000 feet.

Figure 4. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on combustion efficiency of rectangular ram jet.

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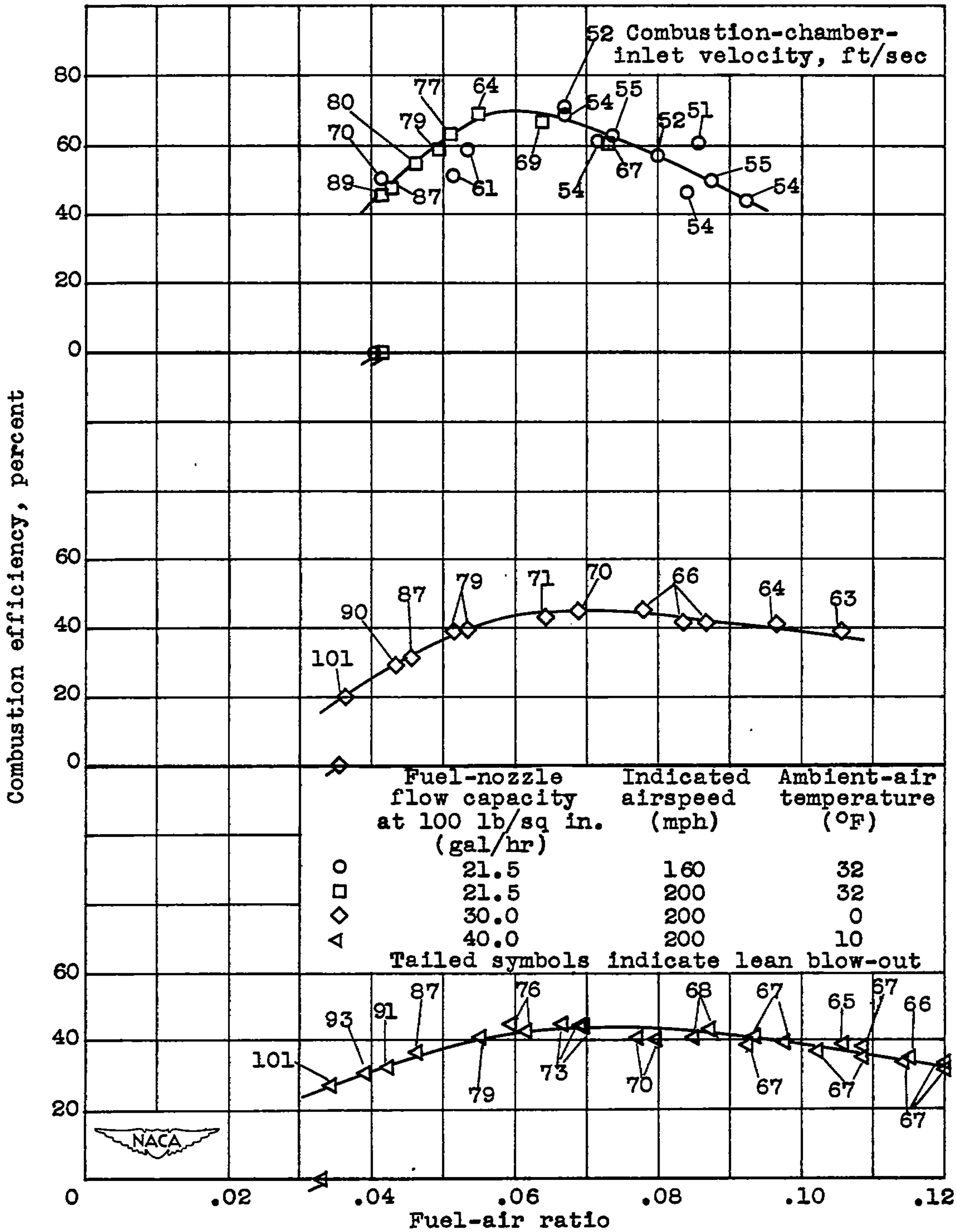
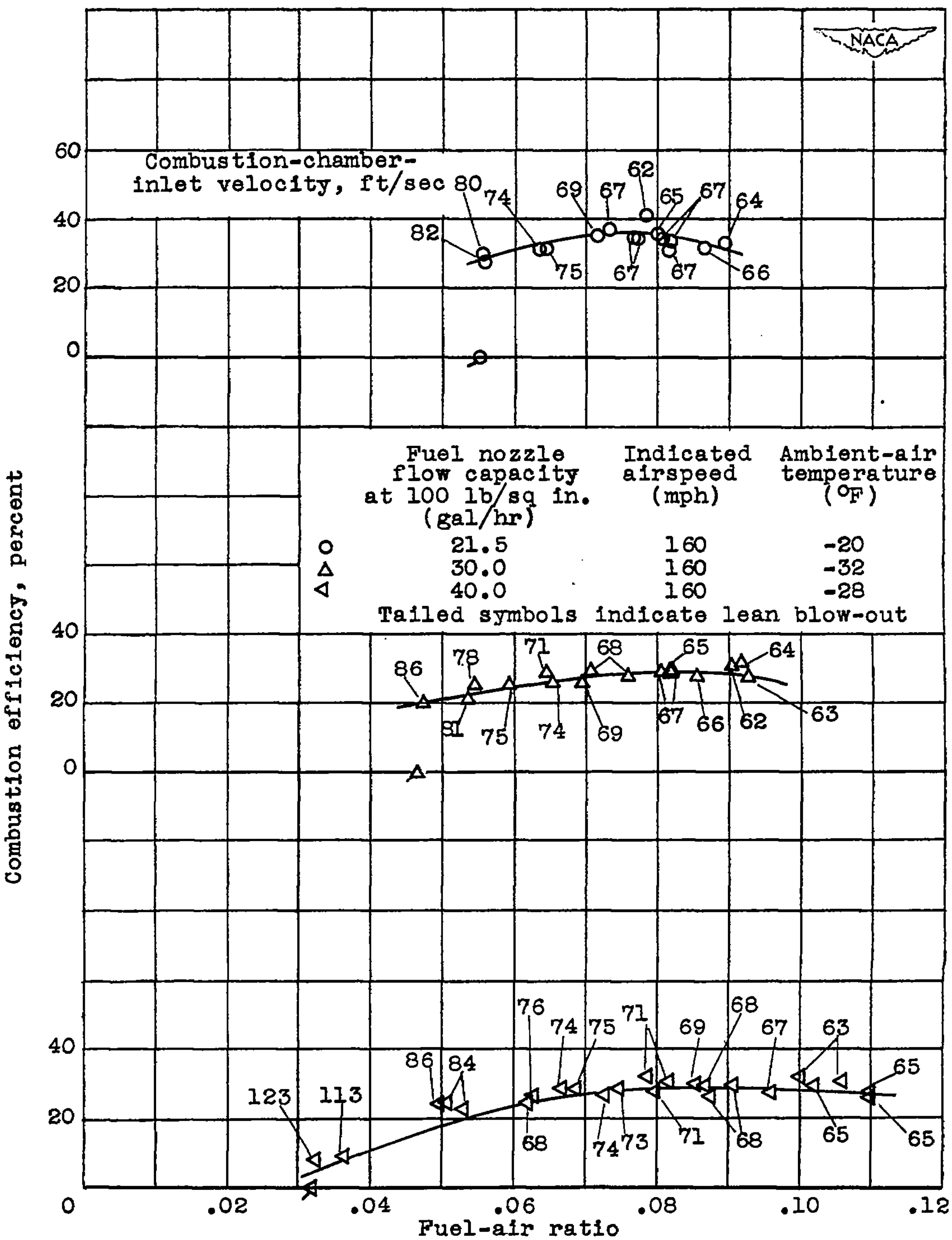


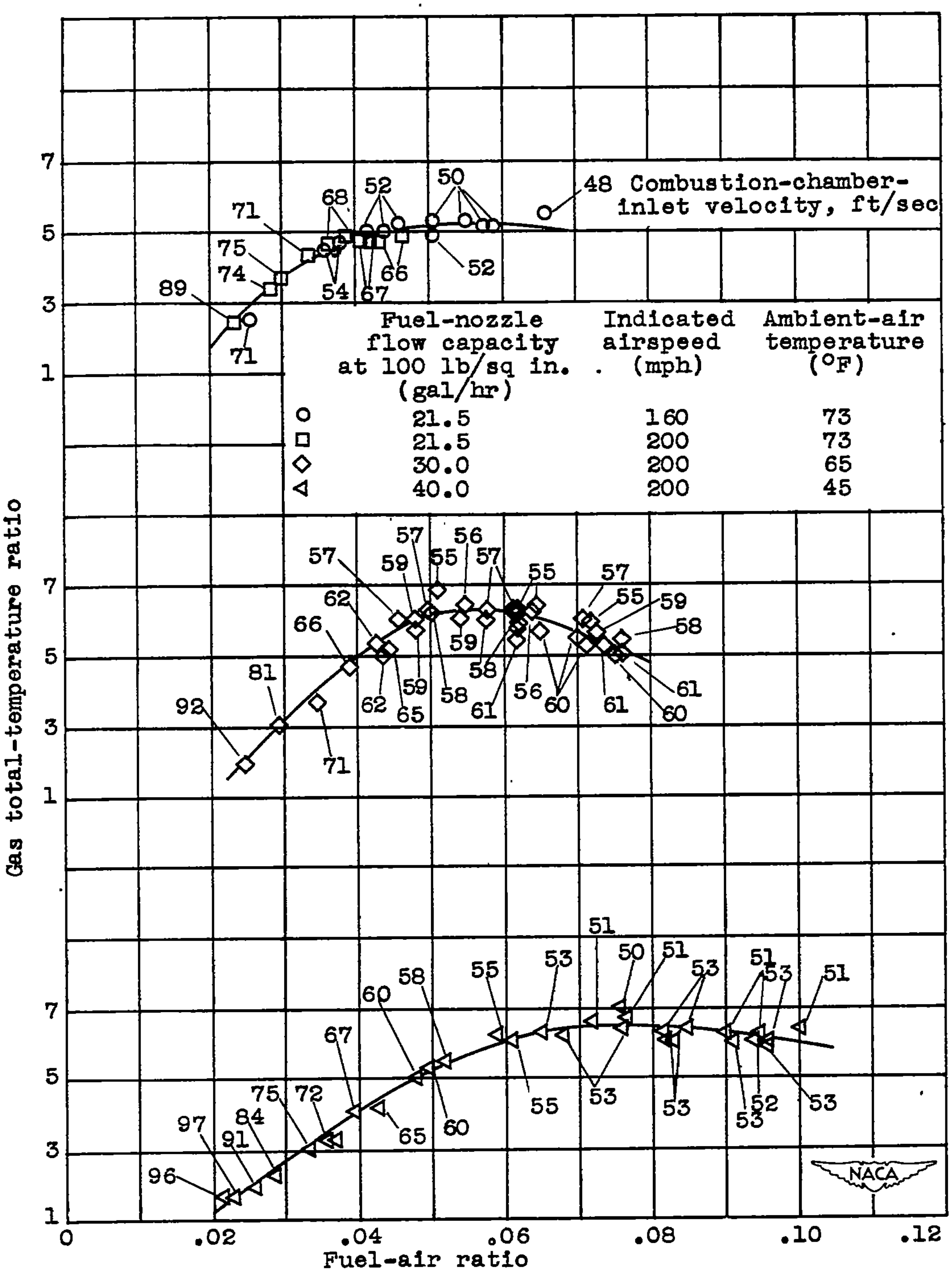
(c) Pressure altitude, 16,000 feet.

Figure 4. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on combustion efficiency of rectangular ram jet.



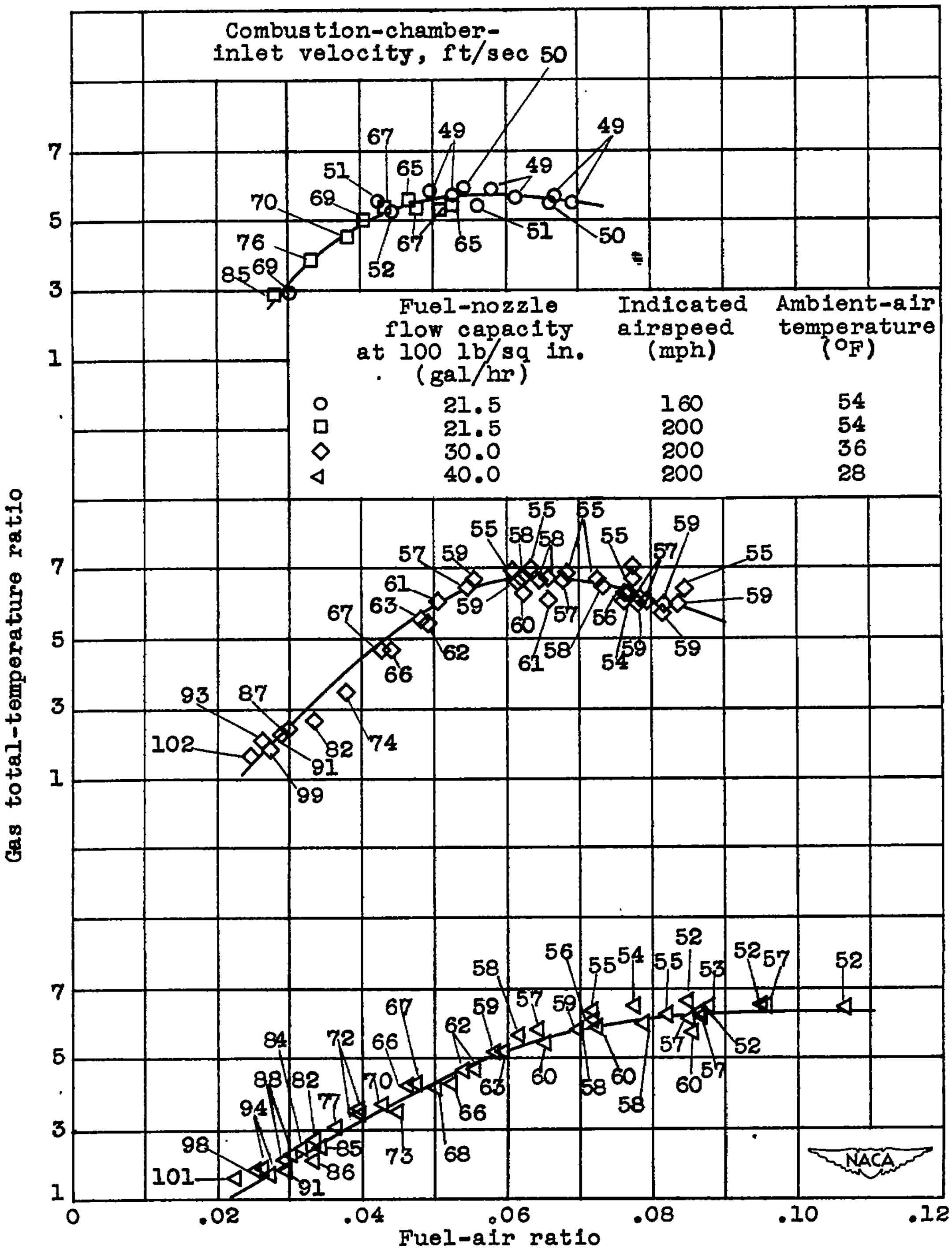
(d) Pressure altitude, 26,000 feet.

Figure 4. - Concluded. Effect of fuel-air ratio and fuel-nozzle configuration on combustion efficiency of rectangular ram jet.



(a) Pressure altitude, 1500 feet.

Figure 5. - Effect of fuel-air ratio and fuel-nozzle configuration on gas total-temperature ratio of rectangular ram jet.



(b) Pressure altitude, 6000 feet.

Figure 5. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on gas total-temperature ratio of rectangular ram jet.

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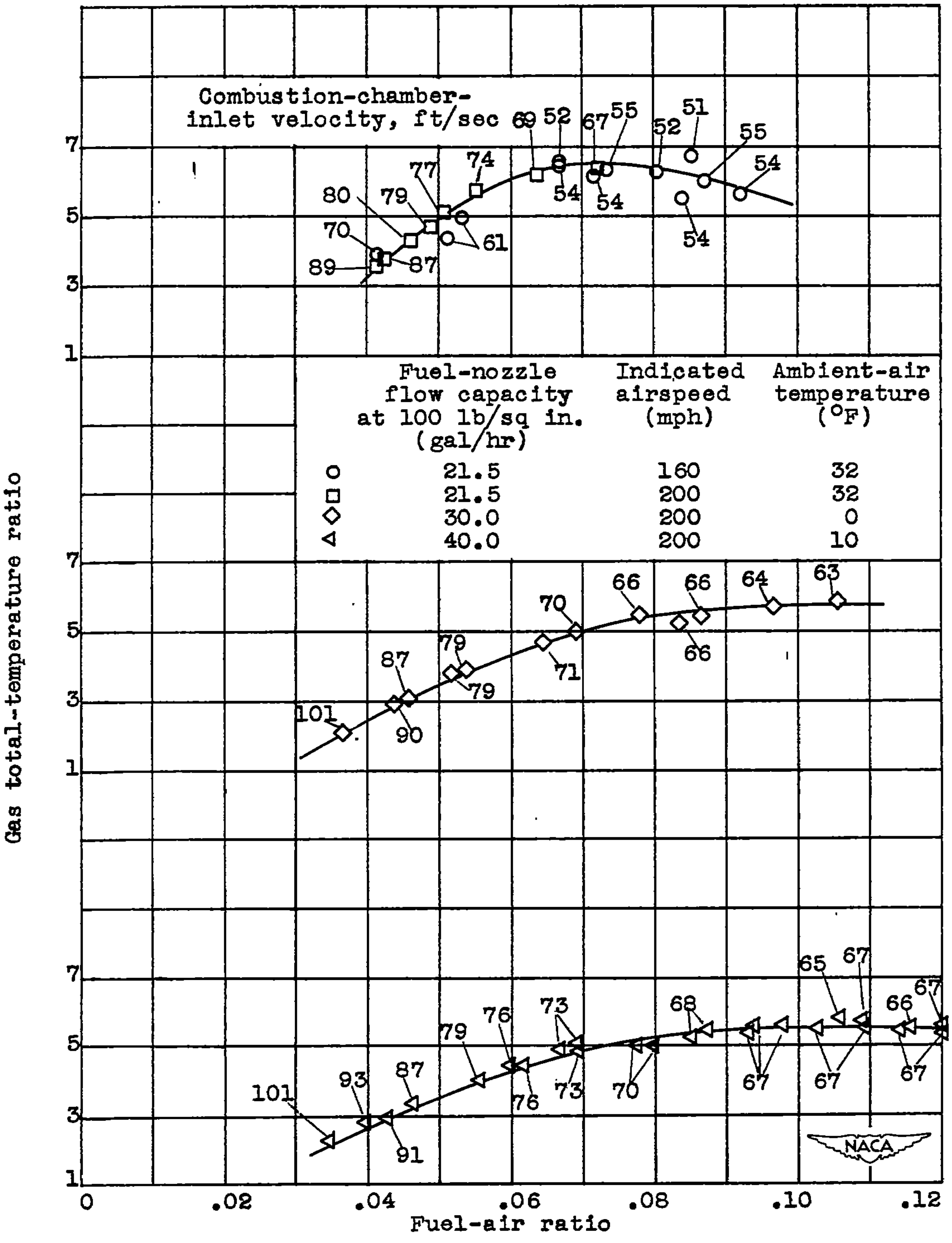
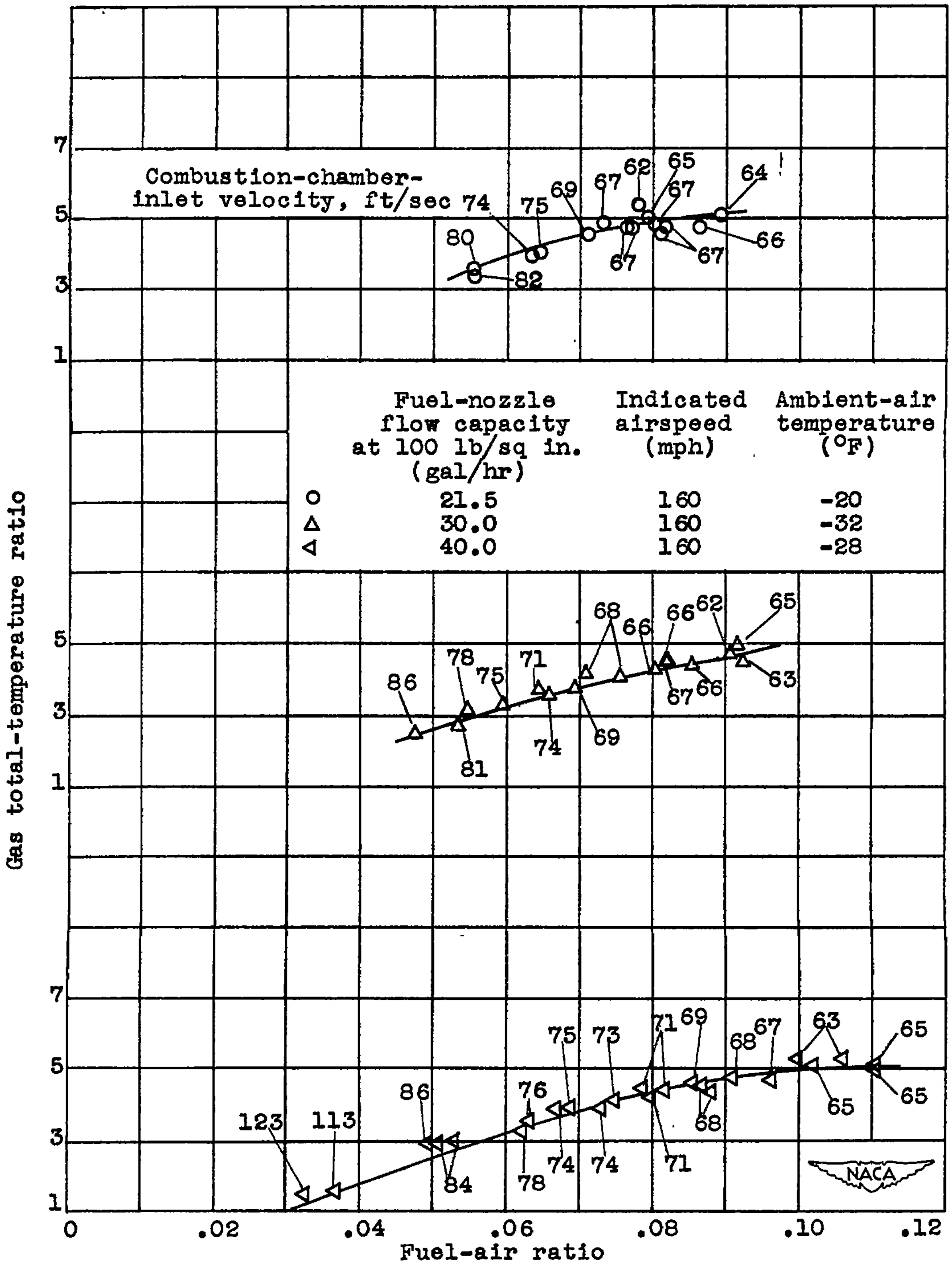


	Fuel-nozzle flow capacity at 100 lb/sq in. (gal/hr)	Indicated airspeed (mph)	Ambient-air temperature (°F)
○	21.5	160	32
□	21.5	200	32
◇	30.0	200	0
◁	40.0	200	10

(c) Pressure altitude, 16,000 feet.

Figure 5. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on gas total-temperature ratio of rectangular ram jet.



(d) Pressure altitude, 26,000 feet.

Figure 5. - Concluded. Effect of fuel-air ratio and fuel-nozzle configuration on gas total-temperature ratio of rectangular ram jet.

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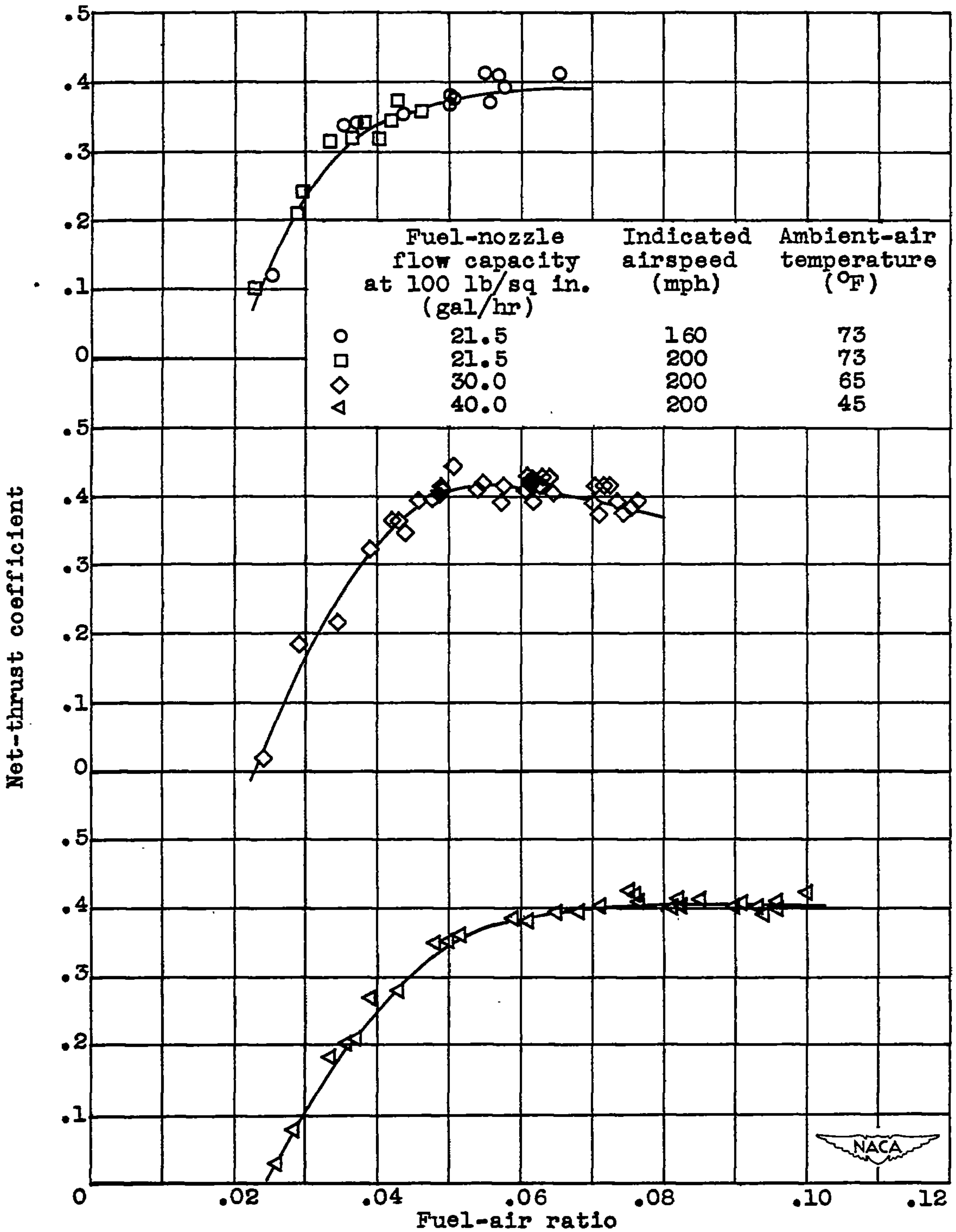
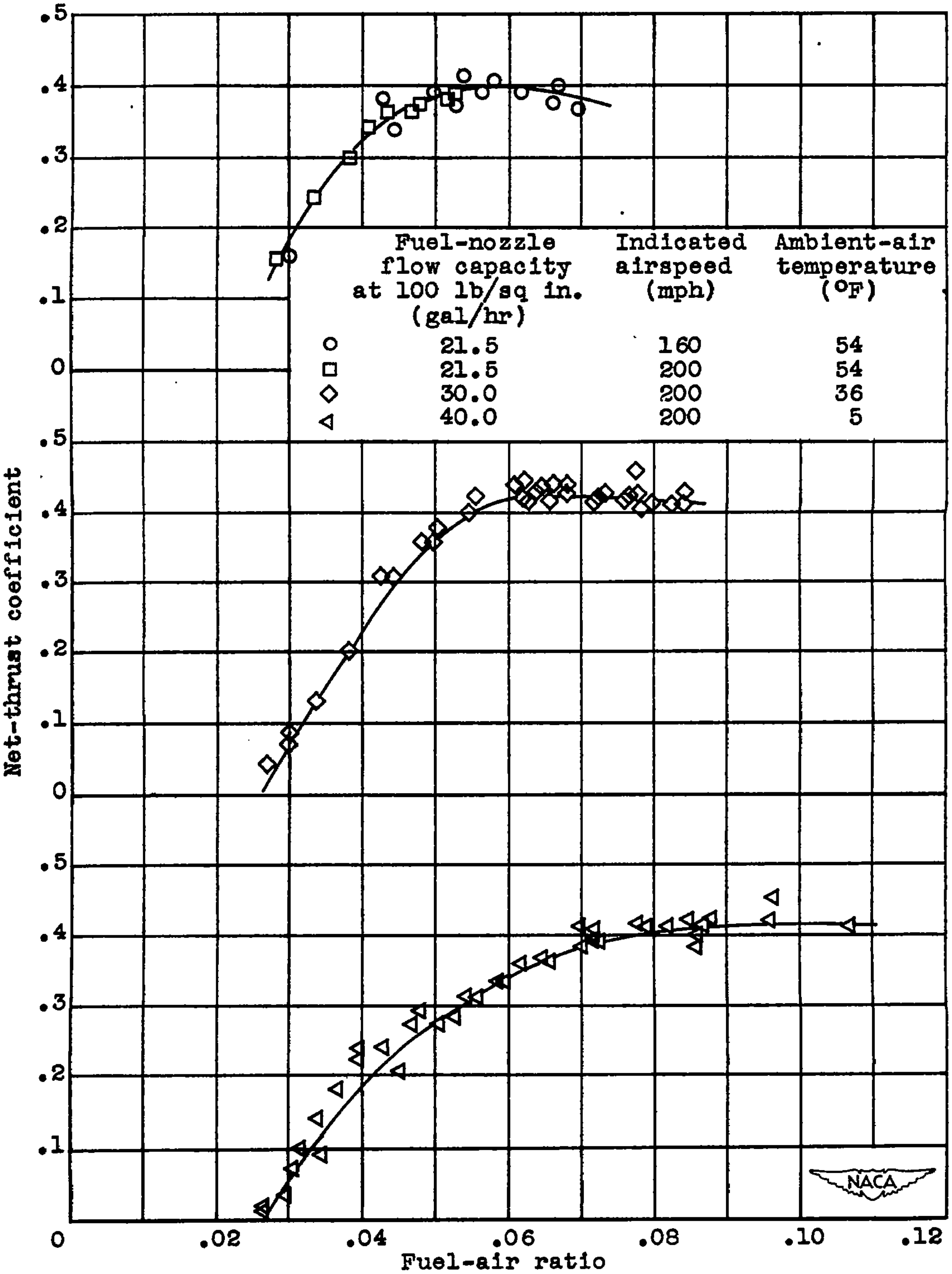


(a) Pressure altitude, 1500 feet.

Figure 6. - Effect of fuel-air ratio and fuel-nozzle configuration on net-thrust coefficient of rectangular ram jet.



(b) Pressure altitude, 6000 feet.

Figure 6. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on net-thrust coefficient of rectangular ram jet.

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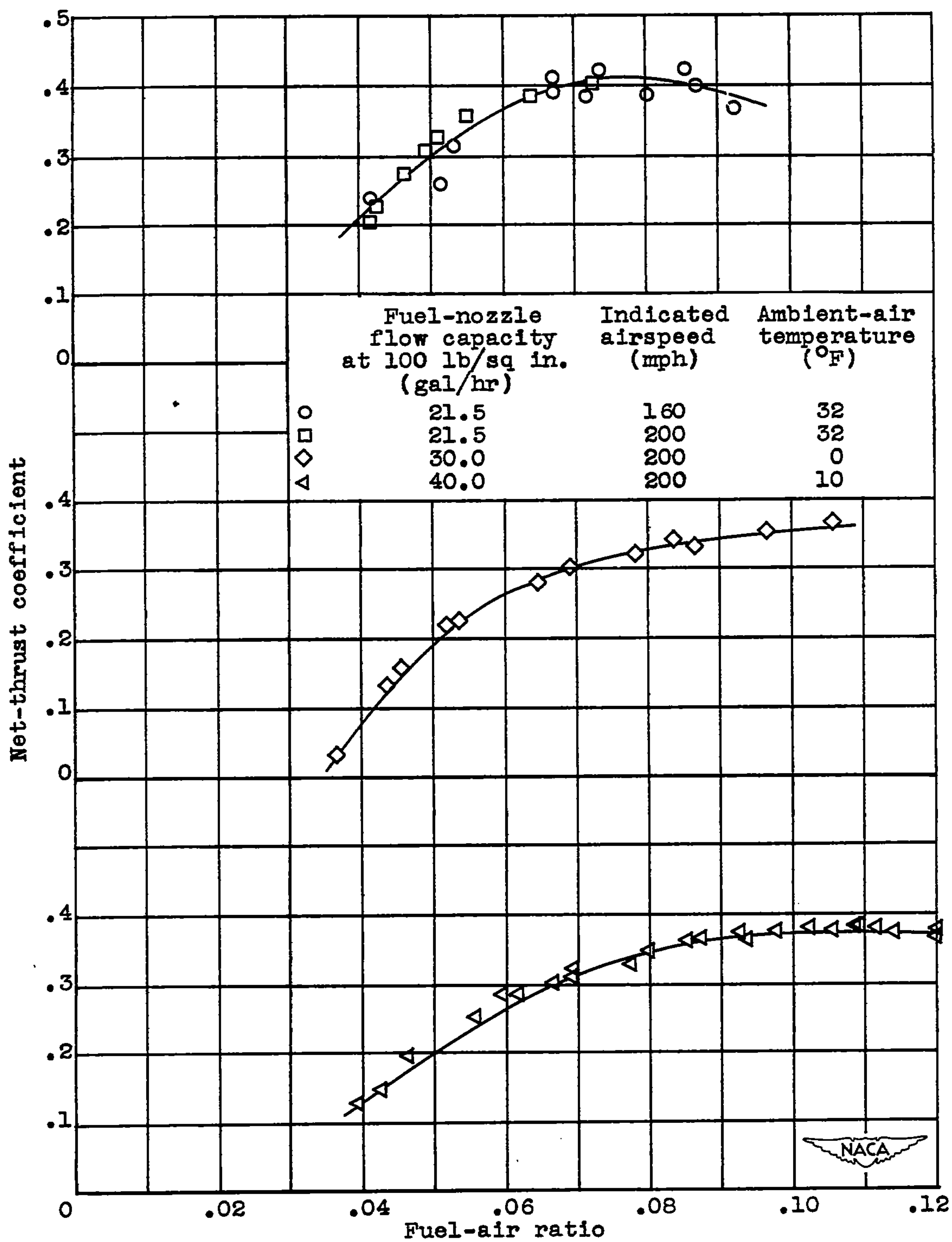
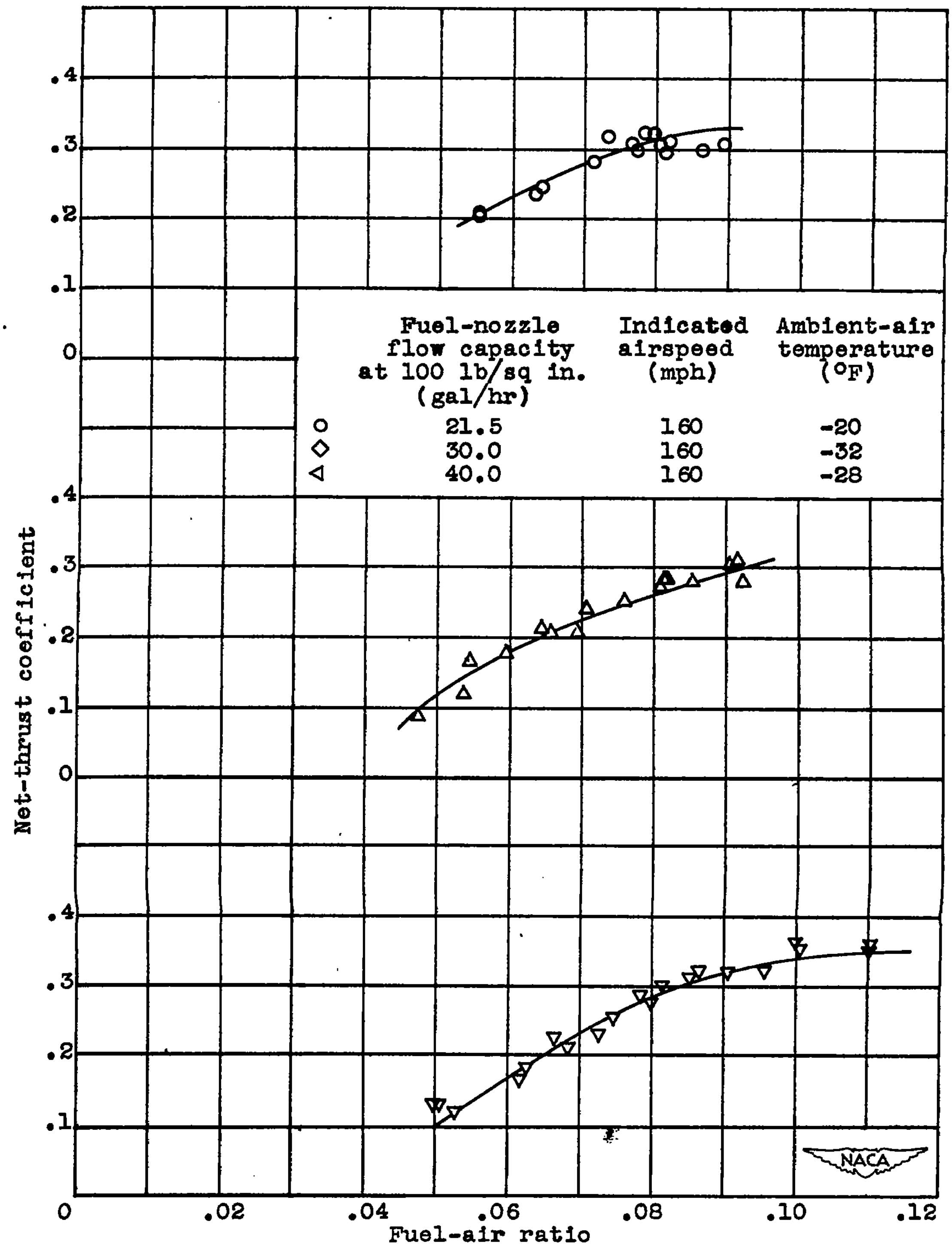


(c) Pressure altitude, 16,000 feet.

Figure 6. - Continued. Effect of fuel-air ratio and fuel-nozzle configuration on net-thrust coefficient of rectangular ram jet.



(d) Pressure altitude, 26,000 feet.

Figure 6. - Concluded. Effect of fuel-air ratio and fuel-nozzle configuration on net-thrust coefficient of rectangular ram jet.